Hybrid Beamforming Design for ISAC Systems via Quantized ZF Filter

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Abstract

In this paper, we propose a hybrid beamforming (HBF) scheme for MIMO integrated sensing and communication (ISAC) systems, aiming to achieve both high-resolution target sensing and efficient downlink transmission. Precoder is designed via alternating optimization, while a quantized AoD-based ZF filters enables accurate and efficient angle estimation. Simulation results verify that the proposed framework closely approaches fully-digital performance while maintaining low computational complexity.

Index Term – hybrid beamforming, region of interest, integrated sensing and communication

Ⅰ. Introduction

In response to increasing spectral congestion due to the rapid growth of wireless devices, multiple-input-multiple-output integrated sensing and communication (MIMO-ISAC) systems have attracted significant attention [1]. The region of interest (ROI) is considered for radar sensing to enhance robustness against direction mismatches [2]. Besides, by adopting hybrid beamforming (HBF) architectures, these systems reduce hardware complexity and power consumption compared with fully digital approaches [3]. In this paper, we propose a HBF design for ISAC systems, aiming to optimize radar sensing performance in the region of interest (ROI) under communication constraints. Additionally, the sequential scanning method with a quantized zero-forcing (ZF) filter is applied to accurately estimate the angle of departure (AoD) toward the target.

Ⅱ. System Model

As shown in Fig 1, we consider a downlink MIMO-ISAC system where the base station (BS) is equipped with N_{BS} antennas arranged in a half wavelength ULA and employs a total of $N_{\mathrm{RF}} = N_c + 1$ RF chains. N_c RF chains are dedicated to transmitting independent data streams to N_c single-antenna communication users, and one additional RF chain is simultaneously reserved for radar sensing a spatial ROI. For the downlink communication and sensing, the channel matrix with $h_k \in C^{N_{Bs}}$ being the channel vector of user k is given by $H \triangleq \left[h_1^T, h_2^T, \cdots, h_{N_c}^T, h_1^T, \cdots, h_{N_t}^T\right] \in C^{(N_c+N_t)\times N_{BS}}$. The transmitted signal vector is generated through HBF, where the analog and digital precoding matrices are denoted as $\boldsymbol{F}_{\mathrm{RF}} \in C^{N_{\mathrm{BS}}\times N_{\mathrm{RF}}}$ and $\boldsymbol{F}_{\mathrm{BB}} \in C^{N_{\mathrm{RF}}\times N_{\mathrm{RF}}}$, respectively. The received signal at the users and SINR for the n-th user is defined as

$$y_n = h_n^T F_{\mathrm{RF}} F_{\mathrm{BB}} \boldsymbol{s} + n \quad (1)$$

$$\gamma_n = \frac{|h_n^H f_n|^2}{\sum_{i=1,\, i\neq n}^{N_{\mathrm{RF}}} |h_n^H f_i|^2 + \sigma^2} \quad (2)$$

Where n is an additive white Gaussian noise (AWGN) vector satisfying $n \sim \mathcal{CN}\left(0, \sigma^2 I_{N_c+N_t}\right)$, $\boldsymbol{f}_i$ is the i-th beamforming vector corresponding to the i-th RF chain. To satisfy QoS demands, a SINR lower bound is assigned to each user as

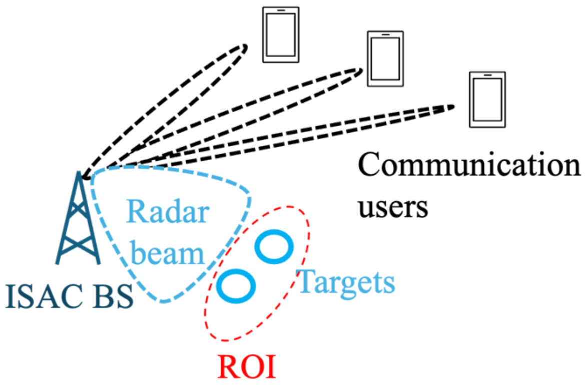

Fig 1. MIMO ISAC system

$\gamma_n \geq \Gamma_n$, where Γ_n is user threshold. Meanwhile, to perform sensing in a ROI, ISAC BS forms beams across angular directions by scanning a predefined angular domain discretized into M point, $\{\phi_1, \phi_2, \ldots, \phi_M\}$. The spatial sampling matrix is defined as

$$\boldsymbol{\Phi} = [\alpha(\phi_1), \alpha(\phi_2), \cdots, \alpha(\phi_M)] \quad (3)$$

and it projects any transmit beam onto sampled directions. The overall transmit beam is the superposition of all beamformers and the goal is to shape this beampattern to match a desired radar response vector $\mathbf{b} \in R^M$ that specifies power distribution across angles. Then the transmit beam design problem can be formulated as

$$\min_{f_1,\ldots,f_{N_{\mathrm{RF}}}} \left\| \left| \Phi \sum_{i=1}^{N_{\mathrm{RF}}} f_i \right| - b \right\|_2 \quad (4)$$

$$\text{s.t.} \quad \sum_{i=1}^{N_{\mathrm{RF}}} \|f_i\|_2^2 \leq P_T, \gamma_n \geq \Gamma_n, \; n = 1,2,\ldots,N_C. \quad (5)$$

subject to a total transmit power constraint and communication SINR constraint.

Ⅲ. Hybrid beamforming design

To solve (4), we adopt the alternating-optimization framework of [4], which effectively decouples the joint optimization of the beamformers and the phase vector. The auxiliary phase vector p controls beam direction. During each step of Alternative Optimization process, we first hold the phase vector p constant With p fixed, we compute the optimize beamformers, $\{f_i\}$ by

Algorithm1 Quantized AoD-Based ZF combiner design

Input : M, N_{RF}, y(received signals), $\boldsymbol{\phi}$(codebook)

Output: Estimated AoDs $\{\widehat{\theta_1}, \cdots, \widehat{\theta_K}\}$

1: Partition M angular directions into [M/N_{RF}] groups.
2: **for** each group i=1,2,,,**do**
3: Construct analog combiner $W_{\mathrm{RF},i}$ using steering vectors. from $\boldsymbol{\phi}$.
4: Apply $W_{\mathrm{RF},i}$ to y and obtain digitized signal y_i.
5: Compute ZF filter:
$W_{\mathrm{BB},i} = \left(W_{\mathrm{RF},i}^H W_{\mathrm{RF},i}\right)^{-1} W_{\mathrm{RF},i}^H$
6: Compute energy spectrum : $s_i = \left|W_{\mathrm{BB},i} y_i\right|^2$
8: **end for**
9: For each user k, find the index m_k with maximum energy in full spectrum.
10: Output estimated AoDs $\widehat{\theta_k} = \theta(m_k)$, where $\theta(m_k) \in \boldsymbol{\phi}$

formulating and solving an second-order-cone program that guarantees both the overall transmit-power constraints and the required SINR levels. This step minimizes the deviation between the achieved and desired beam patterns. Then we update p by solving a constrained least-square problem that projects the current beampattern toward the **b** , followed by element-wise normalization to ensure modulus-constraints on p. These two steps are repeated until convergence. After obtaining the optimal fully-digital precoder via AO framework, we then use Riemannian manifold optimization to split it into its analog and digital parts, $\boldsymbol{F}_{\mathrm{RF}}$, $\boldsymbol{F}_{\mathrm{BB}}$ respectively.

In the receive chain, the monostatic captures signals reflected from the target in the ROI, which are radiated by previously transmitted hybrid precoded beam. The received signal at the BS from k-th user can be expressed as

$$y_k = W h_k h_k^T F_{\mathrm{RF}} F_{\mathrm{BB}} \boldsymbol{s} + n \qquad (6)$$

where the combiner $W = W_{RF} W_{BB}$, used to estimate the target detection, also adopts a hybrid architecture. We apply a quantized AoD-based beam sweeping and zero-forcing (ZF) combining scheme as detailed in Alogirhm2. Specifically, BS sequentially scans the M angular directions using predefined analog beams in blocks of N_{RF}. A digital ZF filter is applied to decorrelate the signals, and the power across all quantized directions is measured. The angle corresponding to the maximum output power is selected as the estimated AoD. The computational complexity scales as

$$\mathcal{O}\left(\mathrm{M}\, \mathrm{N_{RF}}\, \mathrm{N_{BS}} + \mathrm{M}\, \mathrm{N_{RF}^2}\right).$$

which grows proportionally with the grid size M, N_{RF} and N_{BS}.

IV. Simulation results

We consider the simulation the simulation of a MIMO-ISAC system. The system is configured with $N_{\mathrm{BS}} = 512$ antennas and $N_{\mathrm{RF}} = 4$ RF chains, of which three are used for $N_c = 3$ communication users located at angles $\{-\pi/3, -\pi/6, 0\}$, and one is dedicated to sensing. The region of interest (ROI) for sensing spans from $\pi/6$ *to* $\pi/3$, and targets are randomly positioned within ROI. The angular domain is quantized into M=512 directions for AoD estimation. Communication users are subject to a SINR threshold of 10dB, with AWGN power fixed at 0dBm. Figure 2 shows the beam pattern generated. Fig. 2 illustrates the normalized array gain across angles for both the fully-digital precoder $\boldsymbol{F}_{\mathrm{opt}}$ and the proposed hybrid precoder $\boldsymbol{F}_{\mathrm{RF}} \boldsymbol{F}_{\mathrm{BB}}$ under a total transmit power constraint of 30dBm. The three peaks in the figure show the beam directions of three communication users. Due to the modulus constraint of phase shifter, there is energy leakage with HBF, making it slightly worse than which without HBF. As shown in Fig.3, it evaluates the accuracy of target AoD estimation in terms of the normalized mean squared error (NMSE),

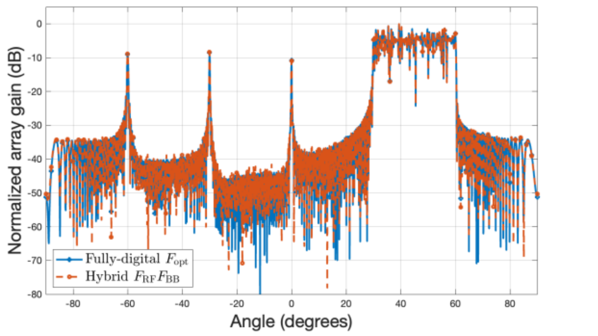

Fig 2. Normalized array gain comparison between F_{opt} & $F_{\mathrm{RF}} F_{\mathrm{BB}}$

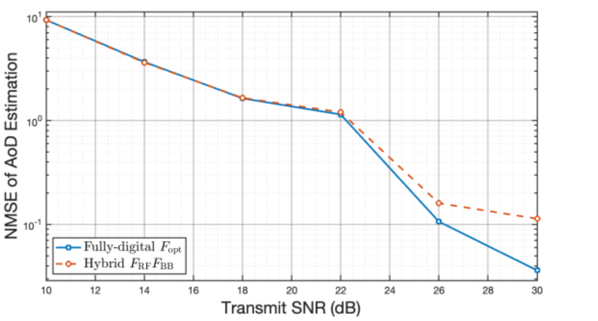

Fig 3. NMSE of target AoD estimation versus transmit SNR

as the transmit SNR varies from 10dB to 20dB. As shown in the figure, NMSE improves consistently with increasing SNR. Notably, the performance of the hybrid precoder closely tracks that of the fully digital precoder across the entire SNR range.

V. Conclusion

In this paper, we proposed a HBF framework for MIMO-ISAC systems that jointly supports downlink communication and high-resolution sensing within a designated region of interest (ROI). Simulation results show the proposed hybrid design achieves high estimation accuracy at sufficiently high SNR, and it maintains low computational complexity by requiring only small matrix inversions per scan.

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